Control of Oscillatory Thermocapillary Convection in Microgravity

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Performance Report for the period

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I. Introduction

The microgravity environment of space provides unique opportunities for the investigation and development of new manufacturing processes and the improvement of existing ones, particularly in cases involving fluid dynamics and transport phenomena. However, because microgravity profoundly alters the interplay among the various flow-producing mechanisms, new scientific challenges can also be anticipated. As a particular example, in terrestrial applications that include the common occurrence of a liquid-gas interface, convection induced by *thermocapillary* forces (due to the temperature variations of a liquid's surface tension) is often confined to small, boundary-layer-like regions while the global transport of heat and other scalar properties is essentially determined by buoyant forces. In contrast, in microgravity, the relative importance of these driving mechanisms is reversed, and the effect of thermocapillary convection is felt throughout the entire flow field (Ostrach 1982).

Liquid-gas interfaces appear in a variety of instances important in the microgravity environment of the Shuttle or the Space Station. Perhaps the broadest category would be those under the heading of *fluid management in space*, which refers to the movement and position control of large and small volumes of liquid. In *materials processing*, such methods as the float-zone crystal-growth process and coating flows are noteworthy. A variety of model problems suggested by the float-zone process have been studied both experimentally and theoretically under both terrestrial and microgravity conditions. In these models, it has been noted that the basic thermocapillary-driven flow can become *unstable*, resulting in the appearance of time-periodic, *oscillatory convection* (Davis 1987). This occurrence has been blamed for the appearance of undesirable striations in material grown by the float-zone process, both in terrestrial and microgravity environments. One may conclude, therefore, that: *i)* thermocapillarity can be a dominant flow-producing force in microgravity environments; and *ii)* thermocapillary convection is subject to instabilities which can have pronounced, undesirable consequences.

The proposed research seeks to design and implement an experimental program to study the active control of oscillatory thermocapillary convection in planar layers. While the thrust of the program is primarily experimental, it is anticipated that supporting numerical work will be necessary to guide and support the laboratory program. This numerical work will be aimed at the development of efficient computational techniques for unsteady, three-dimensional problems of this type.

II. Year 1 Research

A. Experimental Work

Recent progress on this project has been in the following areas, all related to the design of a final apparatus:

i) A preliminary apparatus has been designed and fabricated, based on available data and simple, model calculations.

ii) Experiments have been performed in this apparatus to investigate the establishment of a suitable basic state subject to oscillatory instability. Silicone oils with viscosities of 1 and 2 centistokes were used as the test fluids. These experiments have confirmed, for some layer depths, the appearance of steady, multicellular states observed previously by other experimenters. For other layer depths, however, a steady, unicellular structure is observed. The appearance of the steady, multicellular state is suspected to be due to the influence of buoyancy and is an undesirable feature from the standpoint of control of oscillatory instability. The experiments included the measurement of velocity fields in the layer using a single-component, laser-Doppler velocimeter (LDV). Stream functions constructed from these measurements matched well with the images obtained from flow visualization for both the unicellular and multicellular states. These also provide an indirect technique for the determination of the vertical component of velocity from horizontal component measurements alone.

iii) The two silicone oils to be used in these experiments have been characterized, in the sense that surface tension has been measured over a temperature range which will include temperatures employed in the experiments. These measurements were performed by the Microgravity Advanced Research Support (MARS) Center in Naples, Italy as a courtesy to the Principal Investigator.

iv) The apparatus to be used has been modified to remedy shortcomings observed in the preliminary experiments. These modifications permit more precise control of the depth, among other things, which is necessary due to the profound influence of the dynamic Bond number noted in the earlier experiments. Earlier problems experienced with liquid climbing out of the layer due to capillary action have been overcome through the use of anti-wetting agents.

v) Subsequent experiments performed in the redesigned apparatus, employing both particle/sheet-illumination and shadowgraphic visualization techniques has detected the appearance of oscillatory convection. The transition regimes have been mapped out in Marangoni-Bond-number space. It is also found that the transition to steady, multicellular convection occurs only for larger values of the Bond number; for smaller values associated with thinner layers, the steady, unicellular thermocapillary convection transists directly to oscillatory convection.

B. Theoretical Work

i) The Smith & Davis (1983) theory which originally motivated these experiments has been modified to include the influence of buoyancy. Calculations of stability limits using this theory indicate, as observed experimentally, that there may be a range of dynamic Bond number (and hence, layer depth) for which the earliest appearing instability would be of the oscillatory, hydrothermal-wave variety rather than steady, multicellular flow. The results appear to be in qualitative agreement with the range of parameters for which multicellular flow was absent in the early experiments. Values of the Marangoni number at which oscillations appear are not in quantitative agreement between experiment and theory, but this is presumably due to the use of an "experimental" Marangoni number based on $\Delta T/L$, the overall mean temperature gradient for the apparatus, rather than the more correct dT/dx observed in the core of the layer. The proper value will be available following the acquisition of a digital infrared (IR) camera.

ii) Additional calculations of two-dimensional thermocapillary convection in a laterally heated layer have been performed with the aid of NEKTON, a spectral-element code. The computations yield reasonable results for some conditions and unreasonable ones for others. In some cases, the deformation of the free surface presents the major problem, particularly when attempting computations at high Marangoni numbers. A new Ph.D. student began work in the fall, 1993 quarter on the numerical problem. His time thus far has been spent acquainting himself with the previous work on this problem.

II. Year 2 Research

A. Experimental Work

The newly constructed apparatus will be used further to investigate regimes in which the direct transition from steady thermocapillary convection to oscillatory convection may be possible without passage through the steady, multicellular regime. The use of a digital infrared camera will allow the determination of the surface temperature distribution in the core flow, permitting, in turn, the computation of a more meaningful Marangoni number for comparison with theory.

The control scheme for suppressing oscillatory thermocapillary convection will be implemented. With free-surface temperature data available from the IR camera, it will be possible to provide surface heating to the layer which is out of phase with the surface disturbance temperature.

B. Theoretical

Work on the computation of unsteady, three-dimensional flows with free surfaces will continue in this second year. These are non-trivial problems requiring innovative approaches. The PI continues to communicate/collaborate with Professor H. Mittelmann of Arizona State University, a noted numerical analyst with interests in this area. The most promising approach at the present time, given what has been learned from the NEKTON simulations performed earlier, still appears to be a multi-grid method, since resolution of the flow in some regions proved troublesome.

It was noted above that the original Smith & Davis (1983) analysis had been modified to include the effect of buoyancy. Additional calculations will be performed to check this work and the results will be written up for publication.

References

Davis, S. H. 1987 Thermocapillary instabilities, *Ann. Rev. Fluid Mech.* **19**, 403.

Ostrach, S. 1982 Low-gravity flows, *Ann. Rev. Fluid Mech.* **14**, 313.

Smith, M. K. & Davis, S. H. 1983 Instabilities of dynamic thermocapillary liquid layers. Part 1. Convective instabilities, *J. Fluid Mech.* **132**, 119.

III. Project Personnel

G. Paul Neitzel, Professor, Principal Investigator

R. Jeffrey Riley, Ph. D. Student

David L. Kiesling, Ph.D. Student (NASA GSRP Fellowship Recipient)

IV. Publications and Presentations

Riley, R. J. & Neitzel, G. P., "Steady, Multicellular Flow of Combined Thermocapillary-Buoyancy Convection in a Shallow Horizontal Slot," presented at the Forty-Sixth Meeting of the Division of Fluid Dynamics of the American Physical Society, Albuquerque, NM, November 21-23, 1993

Riley, R. J. & Neitzel, G. P., "Experiments on Multicellular Thermocapillary-Buoyancy Convection," presented at the Winter Annual Meeting of the American Society of Mechanical Engineers, New Orleans, LA, November 28 - December 3, 1993. In *Surface-Tension-Driven Flows*, G. P. Neitzel and M. K Smith, eds., AMD-Vol. 170, American Society of Mechanical Engineers, New York (1993), 75-88.